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How does urbanization affect residential CO_2 emissions? An analysis on urban agglomerations of China

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ABSTRACT

Rapid urbanization has significant effects on China's CO_2 emissions and contributes to climate change. Using a cross–city panel of 64 cities from four large urban agglomerations in China over 2006–2013, we estimate urban household residential energy-related CO_2 emissions. We then apply fixed effects two-stage least squares (2SLS) to explore the relationship between urbanization and residential CO_2 emissions, using an augmented Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model. The results show that the average amount of residential CO_2 emissions in these four agglomerations has a strong increasing trend over 2006–2013, rising from 2.85 to 5.67 million tons (Mt). Those with municipality and capital city status emit more residential CO_2 emissions. A rising urban population share significantly influences residential CO_2 emissions, as does population scale, GDP per capita, urban compactness and the comprehensive level of urbanization. Urban population share has positive effects on residential CO_2 emissions even pasting the demarcation point (75%) in China's urban agglomerations. GDP growth has negative effects on residential CO_2 emissions. Therefore, urban agglomerations' development and expansion should be designed to be well-organized. Policy makers should pay more attention to the urbanization patterns and design a guide for green development and sustainable lifestyle in the process of China's eco-urbanization.

1. Introduction

In recent years, Greenhouse Gas (GHG) emissions, especially CO_2 emissions produced by a large amount of energy consumption in the process of global industrialization, are considered to be the main driving force for global warming (Vakulenko et al., 2016; Anderson et al., 2016; Li et al., 2016). These emissions are a byproduct of economic development. While all countries face issues in balancing energy consumption and environmental protection, these especially matter in emerging economies that are seeking rapid development (Apergis and Payne, 2010; Singh, 2011; Govindaraju and Tang, 2013). As the biggest, and one of the fastest developing countries in the world, China's energy consumption continues to increase in conjunction with the process of rapid industrialization and urbanization. In 2006, China became the world's largest carbon dioxide emitter and its share of global emissions continues to rise (Bai et al., 2017). Due in 2014, CO_2 emissions in China reached 10 billion tons, accounting for almost 30% of global emissions. Moreover, the emissions by China exceed the total amount of US and European Union emissions (Le Quéré et al., 2015).

Accompanied by the intensification of industrialization, urbanization is one of the major consequences of China's economic development. China's urbanization has been at a high speed since the reform and opening up in 1978. The total urban population in China has a strong increasing trend over the period of 1978–2015, rising from 172 million to 771 million. The urban population share rose from 17.9% to 56.1%. It is estimated that the urban population will increase by a further 350 million by 2025 (Deng and Bai, 2014).

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Meanwhile, urban agglomerations have become recognized in recent years and are playing an important role in the process of new-type urbanization in China (Deng et al., 2010). Statistical data reveals that the energy consumption attributed to urban agglomerations accounted for 70.38% (NBSC, 2008). The fast growing population in urban agglomerations intensifies resource demands and intensifies eco-environmental impacts on Chinese cities (Fang and Lin, 2009).

On the other hand, due to the changes in the modes of production and living habits during rapid urbanization process, household energy consumption has increased remarkably. This is causing challenges in balancing the growing requirement of resource utilization and energy consumption (Deng et al., 2016; Wang and Deng, 2017). To be more specific, income growth, rising living standards, and the increasing amount of home appliances, and the demands of housing and private transportation have accelerated residents' energy consumption and increased the amount of residential CO_2 emissions. Recent studies revealed that residential energy-related CO_2 emissions accounted for more than 40% of total carbon emissions in China during 1992–2007 (Liu et al., 2011). Under such circumstances, it is necessary to pay attention to household energy consumption and related residential CO_2 emission, which contributes to formulating energy-saving and GHG emission-reducing policies (Wang et al., 2013a, b). As urban agglomerations are under more enormous pressure to mitigate climate change and reduce CO_2 emissions, it needs badly breakthrough to investigate the relationship between urbanization and household residential energy-related CO_2 emission.

In recent years, there are many studies on the relationship between urbanization, energy consumption, and CO_2 emissions. However, there are still some unresolved issues. Firstly, because of availability of data, most researchers focus on studies at national or provincial level, and are rarely at city level (Miao, 2017). Secondly, more evidence on energy-related CO_2 emissions is needed to explore at sector level and city level. In addition, urban areas in China comprise both urban and rural residences, but most of the existing research does not distinguish between them. Also, few studies focus at agglomeration scale. Moreover, as for the methods, many researchers prefer choosing Index Decomposition Analysis (IDA) and Structural Decomposition Analysis (SDA) to identify the influencing factors of CO_2 emissions (Feng et al., 2012; Wang et al., 2013a, b). But both methods ignore the external effects (e.g. urban development effects, demographic effect, income effects) beyond energy consumption system (Zhang et al., 2017). There are limitations in using these methods to include stochastic shocks, which are helpful to provide evidence for policy implications.

To overcome these limitations, we use a cross-city panel data of 64 cities from four large urban agglomerations: the Pearl River Delta, the Yangtze River Delta, the Beijing-Tianjin-Hebei metropolitan region, and the Chengdu-Chongqing Economic Zone (an upstream area of the Yangtze, comprising Chengdu, Chongqing and surrounding cities) over the period of 2006–2013. We estimate urban residential energy-related CO_2 emissions attributed to electricity consumption, gas consumption, transportation energy consumption and heating consumption. We apply a two-stage least squares (2SLS) fixed effects model to explore the relationship between urbanization and residential CO_2 emissions at urban level based on the augmented Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model. The share of the urban population, urban compactness, which aims to represent the spatial structure of urbanization and emphasize the important role of residents in the built-up areas rather than total urban areas in residential carbon emissions, and a comprehensive indicator of urbanization evaluated from four perspectives - demographic urbanization, economic urbanization, spatial urbanization and social urbanization are introduced to explore the relationship between urbanization and residential energy-related CO_2 emissions.

2. Literature review

In the context of the rapid process of urbanization and the increasing pressure on energy consumption and CO_2 emissions, the studies on the relationship between urbanization and carbon emissions has been brought into focus. However, there is as yet no consensus on the relationship between them. Liddle and Lung (2010) found urbanization had positive correlation to energy consumption and CO_2 emissions in the residential sector in developed countries. Sadorsky (2014) conducted a cross-national analysis and indicated that urbanization continuously increased CO_2 emissions in emerging economies. The similar conclusions on the positive correlations between urbanization and CO_2 emissions can be found in literature (Hiroyuki, 1997; Cole and Neumayer, 2004). Still other researchers think urbanization and carbon emissions change in the relationship is non-linear. Based on the panel data of 88 developing countries during 28 years, Zarzoso and Maruoti (2011) suggested that urbanization had an inverted U-shaped effect on CO_2 emissions and the inverted U-shaped relationship was mainly manifested in high- and middle-income countries. Poumanyvong and Kaneko (2010) explored the relationship between urbanization, energy use and CO_2 emissions in countries of different income level. The results showed that urbanization had negative correlation to energy use in low-income counties but having positive correlation to energy use in high- and middle-income counties, while it has positive effects on emissions in all the countries of different income groups. It can be seen that the relationship between urbanization and carbon emissions is a comprehensive result of both positive and negative effects. Urbanization has positive effects on carbon emissions conditional on the increasing demand of energy, which is often induced by the adjustment of industrial structure and the changes of production modes. When the effects of economic scale and gathering are dominant, urbanization shows negative correlation to carbon emissions (Zhang et al., 2017).

The studies on residents' consumption carbon emissions has gained a lot of attentions from researchers in recent years. Some research focused on the estimation of household energy consumption and carbon emissions/footprints. Chen et al. (2008) found that the compact urban mode reduced household energy consumption. Pachauri and Jiang (2008) conducted household surveys in China and India and compared household energy transitions in these two countries. Others concentrated on exploring the influencing factors of residential CO_2 emissions (Wei et al., 2007; Feng et al., 2011; Wang and Yang, 2016). Satterthwaite (2009) suggested that the increase in consumption scale and consumption level in conjunction with the urbanization process has positive effects on residential CO_2 emissions. Ala-Mantila et al. (2014) applied input-output model to measure household consumption-based carbon footprints and explored the relationship between household types and carbon footprints. The results revealed that a rural lifestyle had positive correlation to GHG emissions. Yuan et al. (2015) estimated indirect residential consumption carbon emissions in China based on the input-output data in 2002 and 2007 and applied SDA model to analyze the impact of urbanization and consumption structure on residential CO_2 emissions. The results showed that urbanization and per capita consumption had positive effects on residential CO_2 emissions. These studies are very significant for policy makers in formulating mitigation policies and achieving a comprehensive understanding of the mitigation policies and their effects.

Most of the studies use IDA and SDA model to explore the explanatory factors of CO_2 emissions. Generally, IDA model divides CO_2 emissions into some components, mainly using Divisia, Lasperyres, Paasche, Fisher, and Marshall—Edgeworth index approaches and their transformations (Wang et al., 2015). It is mainly used to identify the influencing factors such as from the perspective of industries and international trade. It also makes it easy to conduct analysis of time series. Compared with IDA, SDA requires more data and uses the additive form, while IDA chooses both additive and multiplicative forms (Su and Ang, 2012). The results by applying SDA are more complete. The SDA model has been widely used to identify the influencing factors of CO2 emission growth at the global, national and provincial levels (Mi et al., 2017a, b). Feng et al. (2012) applied SDA model to analyze the driving forces of regional CO2 emissions in China based on the regional input-output tables for 2002 and 2007. Xu et al. (2011) applied SDA model to analyze the driving forces of CO2 emissions embodied in China's exports from 2002 to 2008. However, both of IDA and SDA model ignore the external affect. Demographic effects are also considered as an important driving factor for CO_2 emissions respectively using the IPAT model (I = human impact, P = population, A = affluence, T = technology) and STIRPAT model (Martínez-Zarzoso et al., 2007; Kerr and Mellon, 2012; Yao et al., 2015; Liddle, 2013; Wang et al., 2013a, b). Some research also found that international trade has negative effects on CO_2 emissions by employing input-output analysis (Mongelli et al., 2006; Fernández-Amador et al., 2016) and Cointegration and Granger Causality Tests (Jayanthakumaran et al., 2012; Kohler, 2013). Compared with these methods, the STIRPAT model is more widely adopted such as Sadorsky (2014), Li and Lin (2015) and Shahbaz et al. (2016).

3. Study areas

Fig. 1 shows the distribution of the 64 prefecture-level cities in the four urban agglomerations that we study: the Pearl River Delta, the Yangtze River Delta, the Beijing-Tianjin-Hebei metropolitan region, and the Chengdu-Chongqing Economic Zone. Each agglomeration includes one or two municipalities (roughly equivalent to a province) and a further six provinces are touched upon by these areas.

4. Data and methods

4.1. Estimation of urban residential CO_2 emissions

We apply a bottom-up calculation method to estimate direct residential energy-related CO_2 emissions in four steps, following IPCC (2006) (Table 1).

4.2. Empirical models

The Influence, Population, Affluence, and Technology (IPAT) model, first proposed by Ehrlich and Holdren (1971), is widely used to examine the effects of human activities on the environment:

$$I = P \times A \times T \tag{1}$$

where I is environmental impact, P is population size, A is affluence, and T is technological progress.

However, the accounting equation has limitations in not allowing hypothesis testing and in assuming a unified elasticity of the factors (York et al., 2003). Therefore, the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model was proposed, based on the IPAT model (Dietz and Rosa, 1997):

$$I_{it} = a_i P_{it}^b A_{it}^c T_{it}^d e_{it} \tag{2}$$

where a is the constant term and e is the random error term. b, c and d are respectively the elasticity of P, A and T. The suffix i ($i = 1, 2, \ldots, n$) is cities. The suffix t ($t = 1, 2, \ldots, T$) is the time period. To reduce heteroscedasticity, we take both sides of Eq (2) as a logarithm:

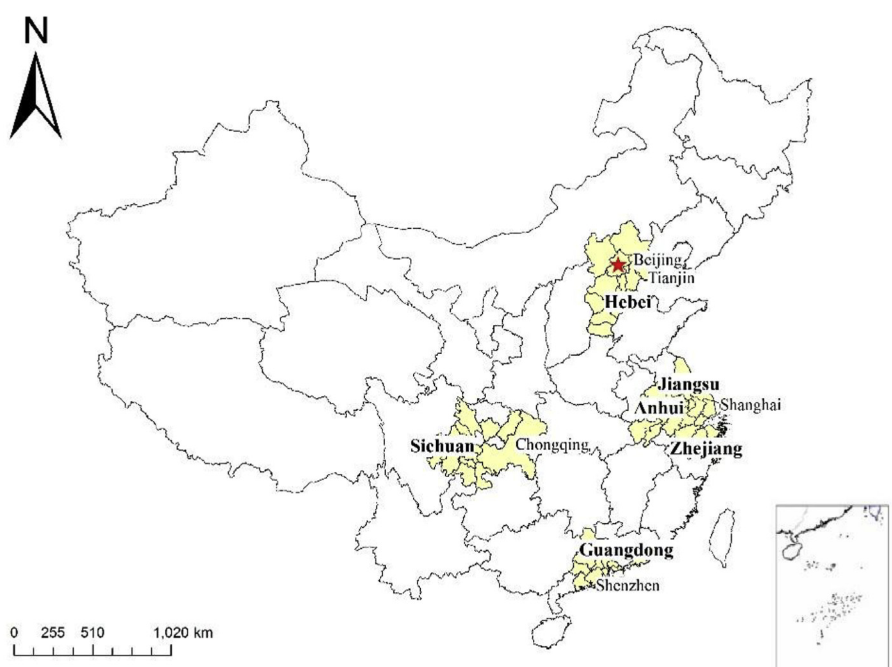

Fig. 1. The distribution of sample prefecture-level cities.

Table 1
Calculation method of direct residential energy-related CO_2 emissions.

CO_2 emissions sources	Calculation formula	Illustration
CO_2 emissions due to residential electricity consumption	$C_1 = E_1 \times K_1$	C_1 is CO_2 emissions due to residential electricity consumption. E_1 is residential electricity consumption (kw·h). K_1 is CO_2 emission coefficient in the power grid of the region (tons/kw·h).
CO_2 emissions due to residential gas consumption	$C_2 = G_1 \times CV_1 \times K_2 + G_2 \times CV_2 \times K_3 + G_3 \times CV_3 \times K_4$	C_2 is CO_2 emissions due to residential gas consumption. G_1, G_2, G_3 are respectively residential Liquefied Petroleum Gas (LPG) consumption (tons), residential natural gas consumption (m^3) and residential coal gas consumption (m^3); CV_1, CV_2, CV_3 are respectively heat value of LPG, natural gas and coal gas, which are respectively 50179 kJ/kg, 38931 kJ/m^3, 16726 kJ/m^3. K_2, K_3, K_4 are respectively CO_2 emission coefficients of LPG, natural gas and coal gas, which are respectively 63100 kgCO_2/TJ, 56100 kgCO_2/TJ and 44400 kgCO_2/TJ.
CO_2 emissions due to residential transportation energy consumption	$C_3 = Q_1 \times L_1 \times \lambda_1 \times k_1 + Q_{21} \times L_2 \times \lambda_2 \times k_2 + Q_{22} \times L_2 \times \lambda_2 \times k_3 + Q_3 \times L_3 \times \lambda_3 \times k_3$	C_3 is CO_2 emissions due to residential transportation energy consumption. Q_1, Q_{21}, Q_{22}, Q_3 are respectively the number of buses, gas-fired taxies, gasoline-fired taxies and private vehicles. L_1, L_2, L_3 are respectively the annual mileage of bus, taxi and private vehicle. λ_1, λ_2, λ_3 are respectively the fuel coefficient of bus, taxi and private vehicle (L/100 km). k_1, k_2, k_3 are respectively CO_2 emission coefficients of diesel, natural gas and gasoline, which are respectively 2.73 kg/L, 2.09 kg/m^3 and 2.26 kg/L.
CO_2 emissions due to residential heating consumption	$C_4 = A \times H \times K_5$	C4 is CO_2 emissions due to residential heating consumption. A is heating area (m^2). H is heating coal consumption per unit area (kg/m^2). K_5 is the CO_2 emission coefficient of standard coal, which is 2.46 kg/kg.
residential energy-related CO_2 emissions	$C = C_1 + C_2 + C_3 + C_4$	C is the direct residential energy-related CO_2 emissions.

Note: Emission factors are very important for this approach (Mi et al., 2017a, b). CO2 emission factors for electricity (K_1) in the power grid of the regions are derived from Baseline Emission Factors for China Regional Power Grid. The annual mileage and the fuel coefficient of bus, taxi and private vehicle is referred to Wang et al. (2008). The heating coal consumption per unit area is calculated according to the Civil Building Energy-saving Design Standard (Heating Residential Building Part) in China.

$$\ln I_{it} = \ln a_i + b \ln P_{it} + c \ln A_{it} + d \ln T_{it} + e_{it} \quad (3)$$

In order to clarify the impact of urbanization on residential energy-related CO_2 emissions, we add urbanization effects (urban) into an augmented STIRPAT model.

$$\ln I_{it} = \ln a_i + b \ln P_{it} + c \ln A_{it} + d \ln T_{it} + \theta \ln urban_{it} + e_{it} \quad (4)$$

We also incorporate population effects, economic effects and urban space development pattern effects into the augmented STIRPAT model. We use the indicators of total population (pop) and GDP per capita (gdp) to reflect the impacts of demographic and economic changes. Urban compactness (com) is defined as the ratio between built-up area to urban area to reflect urban development patterns. GDP growth (gdpg) and CO_2 emission structure (struc), which is defined as the ratio of CO_2 emissions from residential electricity consumption to total residential CO_2 emissions, are also considered in our models. The extended empirical model is as follows:

$$\ln carbon_{it} = a + \theta_1 \ln pop_{it} + \theta_2 \ln gdp_{it} + \theta_3 \ln gdpg_{it} + \theta_4 \ln com_{it} + \theta_5 \ln struc_{it} + \ln urban_{it} + \lambda_t + \gamma_i + e_{it} \quad (5)$$

where γ_i and λ_t describes the individual effects and time effects, α is constant term and e_{it} is the residual error term.

In addition, we introduce a new urbanization index to do a further robustness test. The index, reflecting a comprehensive level of urbanization, is measured by applying Principal Components Analysis (PCA) from four perspectives: demographic urbanization, economic urbanization, spatial urbanization and social urbanization (Bai et al., 2018). The resulting empirical model is as follows:

$$\ln carbon_{it} = a + \theta_1 \ln pop_{it} + \theta_2 \ln gdp_{it} + \theta_3 \ln gdpg_{it} + \theta_4 \ln com_{it} + \theta_5 \ln struc_{it} + \ln urban2_{it} + \lambda_t + \gamma_i + e_{it} \quad (6)$$

4.3. Data

Data for our panel of 64 prefecture-level cities in the four urban agglomerations come from annual observations over 2006–2013. Data for calculating residential direct energy-related CO_2 emissions are derived from China City Statistical Yearbook (2007–2014), China Urban Construction Statistical Yearbook (2007–2014), China Statistical Yearbook for Regional Economy (2007–2014) and China Energy Statistical Yearbook (2014). Data for identifying the explanatory factors of residential CO_2 emissions such as total population, GDP per capita, GDP growth and urban compactness are derived from China City Statistical Yearbook (2007–2014) and China Urban Construction Statistical Yearbook (2007–2014). Data on urbanization (the share of urban population) is derived from Statistical Yearbooks (2007–2014) for the four municipalities and the six provinces. The descriptive statistics for the variables are in Table 2.

5. Results

5.1. Estimation of urban residential CO_2 emissions

The direct household residential energy-related CO_2 emissions are estimated from four types of energy consumption sources: residential electricity consumption, residential gas consumption, residential heating consumption and residential transportation energy consumption. Fig. 2 shows the spatial distribution of these four types of emissions. Cities with high-CO_2 emissions due to residential electricity consumption, transportation energy consumption and gas consumption are mostly developed cities in urban agglomerations in China, such as the municipalities and provincial capitals of the four agglomerations (Beijing-Tianjin, Shanghai-Hangzhou, Chongqing-Chengdu and Shenzhen-Guangzhou). These cities are in the process of substantial economic development and residents' income improvement, resulting in increasing demand for residential appliances (e.g. televisions, computers, refrigerators, air conditioners, washing machines, etc.) and private and public transport. In addition, cities with high CO_2 emissions attributing to residential heating consumption are

Table 2
Descriptive statistics of variables.

Variable	Unit	Obs	Mean	Std.Dev	Min	Max
Population (pop)	10^4 persons	512	218.86	301.01	29	1787
GDP per capita (gdp)	Yuan	512	50998.33	28408.32	7701	158428
GDP growth (gdpg)	%	512	112.84	2.81	101	132.9
Urban compaction (com)	%	512	12.87	12.11	0.74	70.26
CO_2 emission structure (struc)	%	512	38.40	14.05	8.68	70.50
Urbanization (urban)	%	512	53.92	16.88	25.2	100
Urbanization index (urban2)		512	3.42	1.17	2.26	8.75
Residential CO_2 emission (carbon)	10^4tons	512	414.60	700.61	15.58	5090

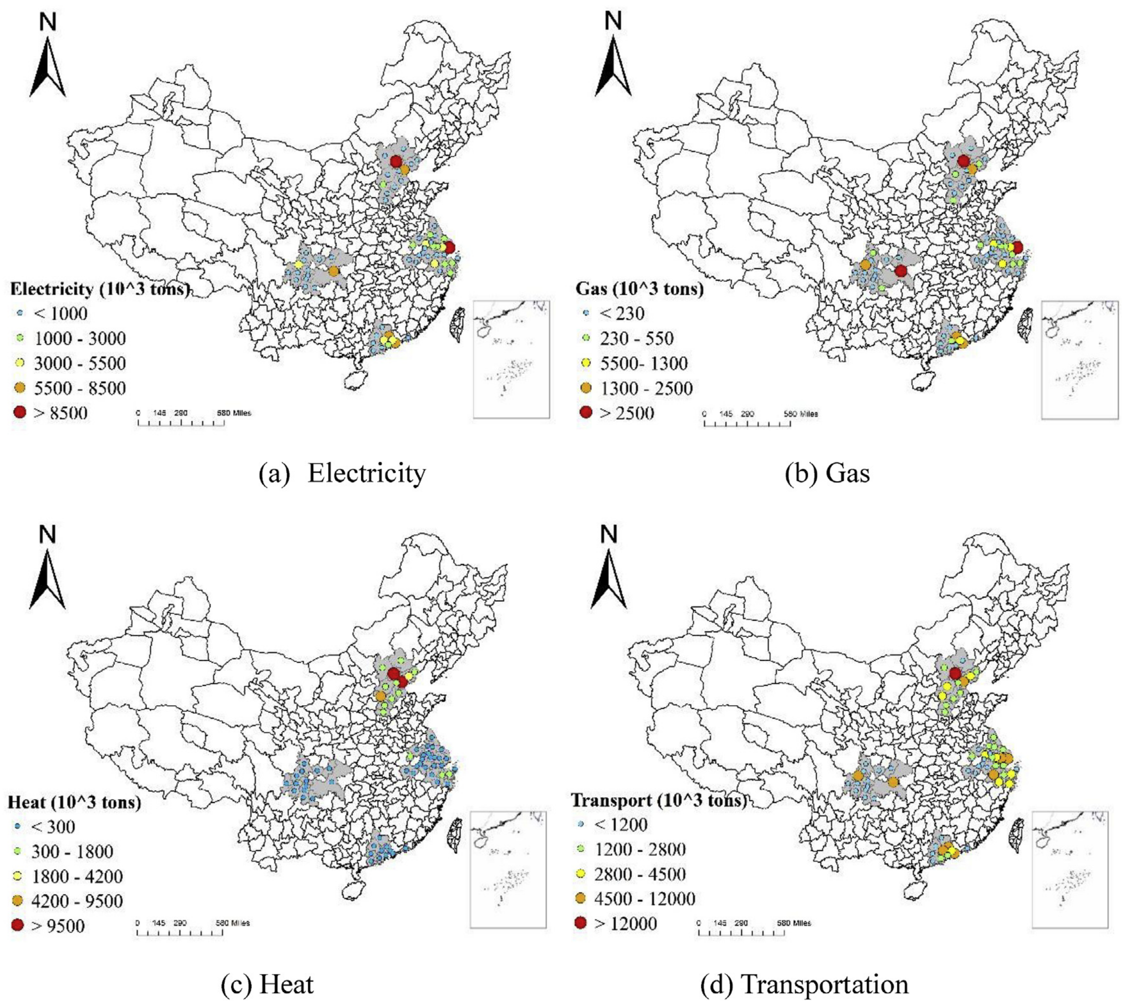

Fig. 2. Spatial distribution of the residential CO_2 emissions due to residential electricity (a), gas (b), heating (c), transportation (d) consumption of urban agglomerations, China in 2013.

mainly located in the Beijing-Tianjin-Hebei metropolitan region in northern China.

The total residential energy-related CO_2 emissions from these 64 cities have a strong increasing trend over 2006–2013, rising from 2.85 to 5.67 million tons (Mt). From the spatial distribution (Fig. 3), it appears that the municipalities and the capital cities in Chinese urban agglomerations in the Pearl River Delta, the Yangtze River Delta, Chengdu-Chongqing Economic Zone, and the Beijing-Tianjin-Hebei metropolitan region emit more residential CO_2 emissions. The residential CO_2 emissions of different urban agglomerations has shown substantial increase during 2006–2013 (Fig. 4). On the whole, CO_2 emissions in Beijing-Tianjin-Hebei metropolitan region exceed those in the Yangtze River Delta, Pearl River Delta and Chengdu-Chongqing Economic Zone. However, since 2012 CO_2 emissions from the Yangtze River Delta have exceeded those from the Beijing-Tianjin-Hebei metropolitan region, possibly because Beijing Municipal Government formulated the planning on energy-saving and cost-reducing and combating climate change for the Twelfth Five-Year Plan Period in 2011. The results suggest that residential CO_2 emissions have increased with urban development. High-CO_2 emission cities and urban agglomerations are consistent with the regional characteristics of larger population scale, greater affluence and larger urban scale.

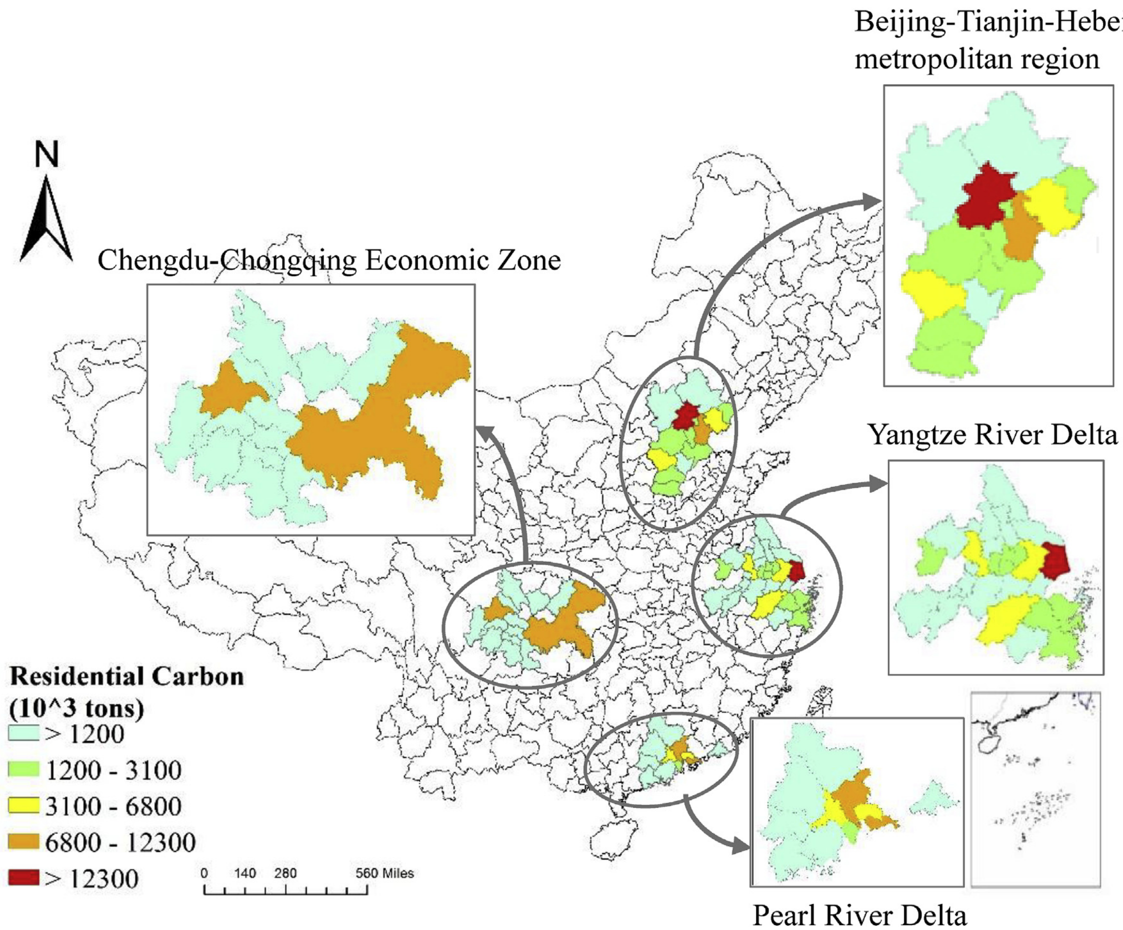

Fig. 3. Spatial distribution of the household residential CO_2 emissions of urban agglomerations, China in 2013.

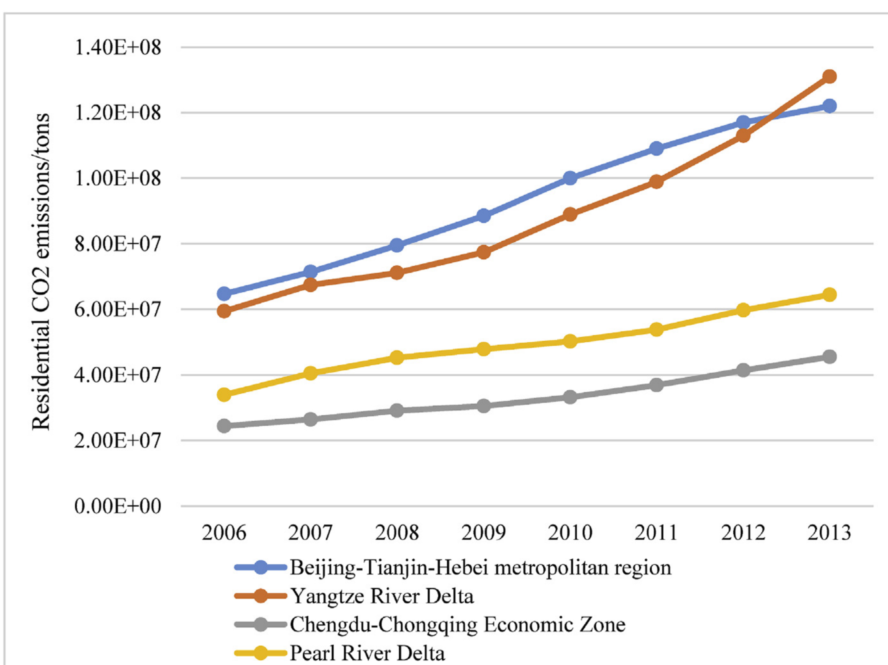

Fig. 4. Household residential CO_2 emissions of urban agglomerations, China during 2006–2013.

5.2. Empirical results

We firstly test the multicollinearity of independent variables when we apply the multiple regression models. Table 3 shows the correlation matrix for the independent variables. As it is presented, the correlation coefficients between different independent variables are below 0.7 except the correlation coefficients between GDP per capita and urbanization. We use the variance inflation factor (VIF) to further test for multicollinearity. The VIF values are much less than 5, which suggests that there should be no problem with multicollinearity in the multiple regression model.

In this paper, we define residential CO_2 emissions (carbon) and residential CO_2 emissions per capita (pcarbon) as dependent variables. The results of Hausman tests reject the null hypothesis of a random effects model, at the 1% significance level. Therefore, we apply fixed-effect models to explore how urbanization affects residential energy-related CO_2 emissions. Table 4 show the estimation results. It reveals that urbanization has positive effects on residential CO_2 emissions, with elasticities of 0.575 and 0.380 for total and per capita emissions, respectively. Population scale is positive correlation to residential energy-related CO_2 emissions and is significant at 1% level. GDP per capita also has positive effects on residential energy-related CO_2 emissions, taking the value of 0.802 for the effects on residential CO_2 emissions and 0.667 for the effects on residential CO_2 emissions per capita. Meanwhile, the relationship between GDP growth and residential energy-related CO_2 emissions is significantly negative, implying that every 1% increase of GDP growth results in a 0.890% decrease in residential CO_2 emissions and a 0.675% decrease in residential CO_2 emissions per capita. These research results are consistent with Environmental Kuznets Curze (EKC) theory (Kaika and Zervas, 2013). In addition, urban compactness positively influences residential CO_2 emissions per capita and is significant at the 1% level.

To address the potential problem of endogeneity of regressors, we apply two-stage least squares (2SLS) estimation in Table 5. We use the one-year lagged value of urban compactness as the instrumental variable for urban compactness. Because the one-year lagged value of urban compactness correlates very highly with current urban compactness. But current residential CO_2 emissions cannot affect former urban compactness. As shown in Table 5, the results of Anderson canon. corr. LM statistic, Cragg-Donald Wald F statistic and Sargan statistic indicate that the model pass underidentification test, Weak identification test and overidentification test. Therefore, the instrument variable is appropriate in the fixed effects 2SLS. As shown in Tables 4 and 5, the empirical results are still quite robust. It appears that urbanization has positive effects on residential CO_2 emissions, as does population scale and GDP per capita. The relationship between GDP growth and residential CO_2 emissions is significantly negative, implying that the environmental Kuznets curve (EKC) holds (Kaika and Zervas, 2013), which is also consistent with Zhang et al. (2017). In addition, a rising urban compactness significantly positively influences the increase in residential CO_2 emissions per capita.

Table 3
Correlation matrix.

	Urban	pop	gdp	gdpg	com	struc
struc	1					
Pop	0.653	1				
Gdp	0.749	0.387	1			
gdpg	−0.248	−0.099	−0.345	1		
Com	0.353	0.210	0.558	−0.245	1	
struc	0.186	0.157	−0.082	0.294	−0.418	1

Notes: values of all the variables are standardized by taking a natural logarithmic transformation.

Table 4
Basic model.

	carbon	pcarbon
Pop	0.409***	
	(0.293, 0.525)	
Gdp	0.802***	0.667***
	(0.689, 0.915)	(0.546, 0.789)
Gdpg	−0.890***	−0.675*
	(-1.541, −0.239)	(-1.394, 0.044)
Com	0.058	0.152***
	(-0.135, 0.129)	(0.075, 0.228)
Struc	−0.040	−0.099**
	(-0.124, 0.045)	(-0.192, −0.007)
urban	0.575***	0.380*
	(0.175, 0.975)	(−0.067, 0.821)
Constant	5.635***	3.670*
	(2.132, 9.136)	(−0.181, 7.521)
N	512	512
R-squared	0.845	0.746
F	402.3	259.88

Notes: values of all the variables are standardized by taking a natural logarithmic transformation. 95% confidence interval in parentheses. *p < 0.1. **p < 0.05. ***p < 0.01.

Table 5
Robust test 1 with 2SLS.

	carbon	pcarbon
pop	0.411	
	(0.279, 0.543)	
gdp	0.782***	0.610***
	(0.633, 0.930)	(0.453, 0.768)
gdpg	−0.750***	−0.743*
	(-1.522, 0.023)	(-1.621, 0.135)
com	0.115	0.290***
	(-0.058, 0.289)	(0.112, 0.469)
struc	0.040	0.115
	(-0.047, 0.127)	(-0.113, 0.086)
urban	0.851***	0.639**
	(0.358, 1.344)	(0.081, 1.196)
N	448	448
Center R-squared	0.824	0.696
F	295.36	174.29
Anderson canon. corr. LM statistic	74.241	84.791
Cragg-Donald Wald F statistic	90.597	107.403
Sargan statistic	0.000	0.000

Notes: values of all the variables are standardized by taking a natural logarithmic transformation. 95% confidence interval in parentheses. *p < 0.1. **p < 0.05. ***p < 0.01.

We further replace urbanization with a new urbanization index to do a further robustness test. This index is estimated by using the PCA method to reflect a comprehensive indicator of urbanization from demographic, economic, spatial and social urbanization. We conduct the robust test and compare the estimated results with the results in Table 3. As is shown in Table 6, the empirical results are still quite robust. Population scale, GDP per capita and urban compactness all increase the residential CO_2 emissions, while GDP growth decreases residential CO_2 emissions.

In addition, we divide the samples into two groups by taking 75% of urbanization, which means a region almost completes the urbanization process, as the demarcation point (Table 7). The results show that urbanization has positive effects on residential CO_2 emissions, as does urban compactness, despite the elasticity of urban compactness for the group with urbanization equal or more than 75% is insignificant. What's more, the elasticity of urbanization is still significantly positive even pasting the demarcation point. Even the elasticity of urbanization of the group with urbanization equal or more than 75% are higher than that of the group with urbanization less than 75%, which is consistent with Zhang et al.

Table 6
Robust test 2 with alternative measure of urbanization.

	carbon	pcarbon
pop	0.462***	
	(0.339, 0.586)	
gdp	0.838***	0.565***
	(0.689, 0.915)	(0.455, 0.674)
gdpg	−1.024***	−1.053***
	(-1.693, −0.355)	(-1.775, −0.331)
com	0.053	0.113***
	(-0.021, 0.125)	(0.036, 0.190)
struc	−0.047	−0.092**
	(-0.132, 0.038)	(-0.182, −0.001)
urban	0.084*	0.216***
	(-0.006, 0.174)	(0.125, 0.308)
Constant	8.069***	8.600*
	(4.254, 11.883)	(4.485, 12.714)
N	512	512
R-squared	0.844	0.755
F	396.74	273.31

Notes: values of all the variables are standardized by taking a natural logarithmic transformation. 95% confidence interval in parentheses. *p < 0.1. **p < 0.05. ***p < 0.01.

(2017). Urbanization has not reached the turning point. The estimation of other variables is basically consistent with results in basic model.

6. Discussion

Based on this research, we have some new findings. First, urbanization has positive effects on household residential energy-related CO_2 emissions. This is measured not only by using the share of urban population, but also by using urban compactness, an indicator reflecting spatial structure of urbanization, and a comprehensive indicator of urbanization, estimated by PCA from four perspectives of demographic urbanization, economic urbanization, spatial urbanization and social urbanization. The positive correlation between the share of the population who are urban, and residential energy-related CO_2 emissions is shown in Fig. 5. This is mainly because urbanization shifts the demands and behaviors of urban households. Urban residents depend on more commercial products and services (Omer, 2008). The ownership of household appliances and heating installation are increasing continuously with speeding up the course of the urbanization, resulting in the growth of energy consumption and related CO_2 emissions (Yuan et al., 2015). Another reason is that urbanization increases the demands for residential private and public transportation, which inevitably leads to emit more CO_2 emissions (Weinberger et al., 2009). The empirical result also shows that urban compactness has positive effects on residential CO_2 emissions. It confirms the previous findings that the increasing quantity of residential appliances and the growth of urban residential areas are closely related, causing the increase of household energy consumption and CO_2 emissions (Fang and Wang, 2013). Besides, the results reveal that population scale and affluence significantly positively affected residential CO_2 emissions, corroborating Zha et al. (2010) and Miao (2017) in other studies for China.

In addition, there are some findings suggesting an inverted U-shaped relationship exists between urbanization and CO_2 emissions (Zarzoso and Maruoti, 2011). Therefore, we also consider the nonlinear relationship between urbanization and residential energy-related CO_2 emissions. However, the estimated coefficients are not significant so we don't present the results in our analysis. In fact, there are also some research results used for reference. Zhang et al. (2017) find that the nonlinear relation between urbanization and CO_2 emissions is not significant in developing countries and it could be that urbanization has not reached the turning point. The results in our research imply that although more and more people migrate to urban areas, residential energy-related CO_2 emissions cannot be reduced in the process of the environmental-unfriendly urbanization. Therefore, it needs the breakthrough to promote the development of eco-urbanization. It shed lights for government to design a guide to green development and sustainable lifestyle, such as technology innovation in heating systems and renewable energy vehicles.

7. Conclusions

Based on a cross-city panel data of 64 prefecture-level cities in four large urban agglomerations of the Pearl River Delta, the Yangtze River Delta, the Chengdu-Chongqing Economic Zone and the Beijing-Tianjin-Hebei metropolitan region over 2006–2013, we estimate urban residential energy-related CO_2 emissions attributed to household residential energy consumption. We divide household residential energy consumption into electricity consumption, gas consumption, transportation energy consumption and heating consumption. We further explore the relationship between

Table 7
Robust test 3.

	urban≥75		Urban < 75	
	carbon	pcarbon	carbon	pcarbon
pop	0.424**		0.421***	
	(0.086, 0.763)		(0.294, 0.548)	
gdp	0.650***	0.411***	0.805***	0.678***
	(0.446, 0.855)	(0.249, 0.572)	(0.674, 0.937)	(0.536, 0.819)
gdpg	−0.898***	−1.005***	−0.925**	−0.711*
	(-1.566, −0.231)	(-1.728, −0.282)	(-1.674, −0.176)	(-1.533, 0.110)
com	0.025	0.045	0.071	0.183***
	(-0.030, 0.081)	(-0.014, 0.103)	(-0.015, 0.157)	(0.092, 0.273)
struc	0.006	0.111	−0.039	−0.097*
	(-0.200, 0.212)	(-0.103, 0.325)	(-0.131, 0.052)	(-0.197, 0.002)
urban	2.782***	4.808***	0.528**	0.292
	(0.962, 4.603)	(3.310, 6.306)	(0.063, 0.993)	(-0.215, 0.801)
Constant	−1.838	−11.202***	5.762**	4.000*
	(-10.071, 6.340)	(-17.862, −4.541)	(1.748, 9.776)	(-0.394, 8.394)
N	72	72	440	440
R-squared	0.962	0.932	0.839	0.740
F	237.03	158.35	328.81	216.08

Notes: values of all the variables are standardized by taking a natural logarithmic transformation. 95% confidence interval in parentheses. *p < 0.1. **p < 0.05. ***p < 0.01.

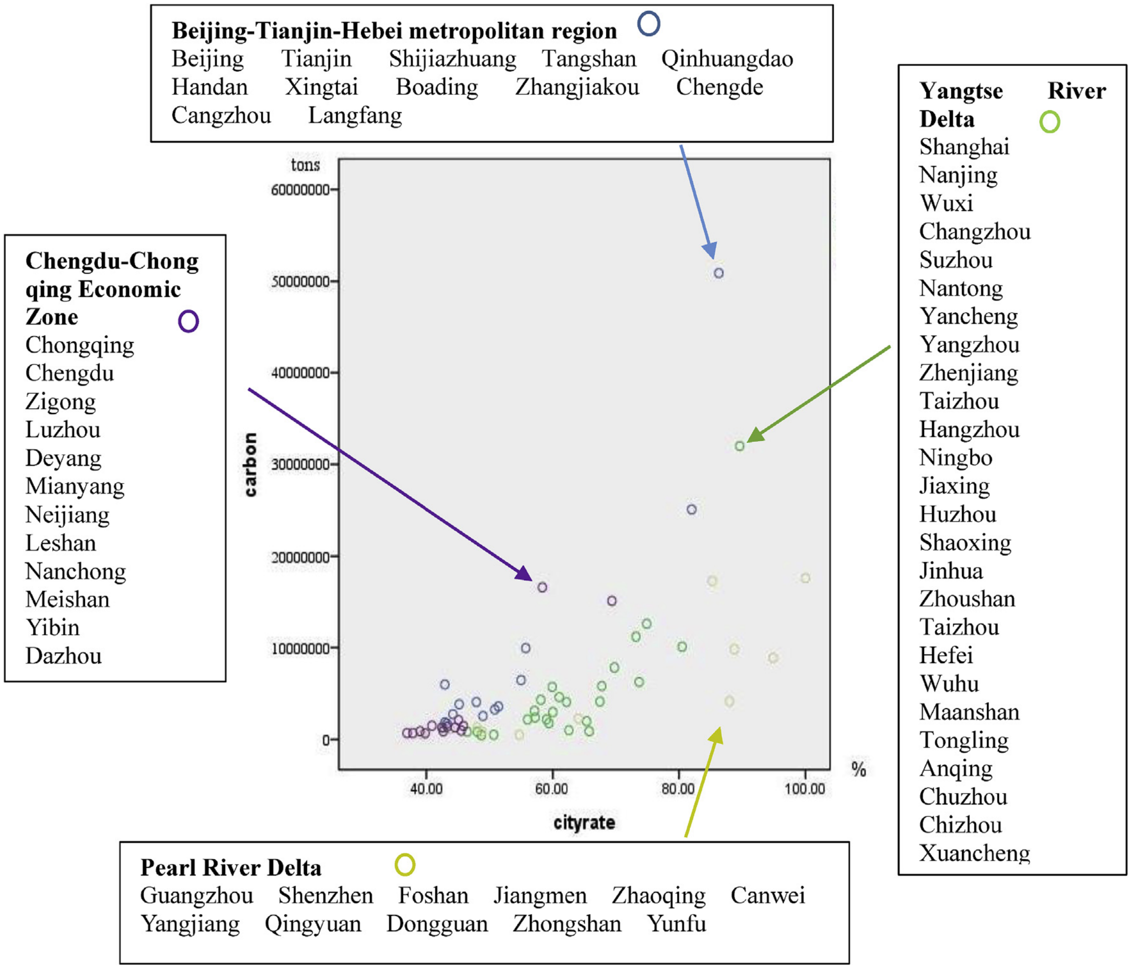

Fig. 5. Relationship between urbanization and household energy-related residential CO_2 emissions in urban agglomerations, China.

urbanization and residential CO_2 emissions by applying fixed effects two-stage least squares (2SLS) models at city level based, on an augmented STIRPAT model. Apart from the share of population who are urban, compactness and a comprehensive indicator of urbanization estimated from demographic, economic, spatial and social urbanization are also proposed as factors that show effects of urbanization on residential CO_2 emissions.

Our research shows that the amount of residential energy-related CO_2 emissions from these cities had a strong increasing trend over 2006–2013, rising from 2.85×10^6 to 5.67×10^6 tons. In terms of spatial distribution, the municipalities and the capital cities in these urban agglomerations emit more residential energy-related CO_2 emissions. The empirical results indicate that the share of urban population exerts positive effects on residential CO_2 emissions. What's more, the increase of the population scale significantly influences the increase in residential CO_2 emissions. GDP per capita significantly positively affects residential CO_2 emissions due to the increasing purchasing power of residents in urban areas. On the contrary, GDP growth has negative effects on residential CO_2 emissions, implying that the EKC theory holds. In addition, we investigate the effect of urban compactness on residential CO_2 emissions. The results show that the share of built-up areas is also positive correlation to residential CO_2 emissions. These findings provide valuable references for promoting low-carbon development in the process of China's eco-urbanization.

In this sense, policy options are provided for promoting green development and enhancing green technology innovations that curb urban residential energy-related CO_2 emissions in the process of China's eco-urbanization. We conclude that government should pay more attention to the urbanization patterns. The benefits of urbanization can be counteracted if the urban agglomerations have an excessive concentration of population. Urban agglomerations' development and expansion should be designed to be well-organized so as to avoid potential congestions problems. In addition, policy makers should pay close attention to designing a guide for green development and sustainable lifestyle, such as green technology innovation in heating systems and renewable energy consumption in transportation, in order to avoid inefficient and environmental-unfriendly urbanization.

Conflicts of interest

The authors declare no conflict of interests.

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Appendix A. Supplementary data

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